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# RADIOIODINE PREDICTION MODEL FOR NUCLEAR TESTS

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16. ABSTRACT

Results of 14 experiments on the air-forage-cow-milk transfer of iodine-131 are summarized and used to develop prediction models for dose to the thyroids of infants. The models are based on data from various types of nuclear tests together with data from controlled experiments using contaminating aerosols. This provides a realistic foundation for the predictions and for adjusting the predictions to correct for some types of forage.

Equations developed from these studies can be used to predict within a factor of 2 the infinite dose to a 2-gram thyroid from a single contaminating event where cows continue to ingest contaminated forage and the subject drinks 0.7 liters of milk per day. This dose, in rads, is equal to 0.37 times the peak exposure rate measured 1 meter above ground, or 0.07 times the integrated air concentration. For wet deposition, it is suggested that the predicted doses be increased by a factor of 10. An equation for pre-test prediction is also developed.

Short-lived radioiodines and inhalation during effluent passage have a definite effect on the predicted doses.

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# RADIOIODINE PREDICTION MODEL FOR NUCLEAR TESTS

by

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# INTRODUCTION

Early in 1963 an Ad Hoc Working Group met at the Nevada Operations Office of the U.S. Atomic Energy Commission (AEC)* to consider the problems associated with radioactive debris from nuclear tests. Of the long-range studies suggested by this Group, the AEC assigned a portion of the responsibility and funds to the U.S. Public Health Service (PHS). As a result, in 1963 the PHS started planning and in 1964 initiated an investigation of the possible hazards to the general human population that might be caused by the release of radioiodine during testing of nuclear devices.

One of the principal objectives of the investigation was to obtain a more precise definition of the air-forage-cow-milk pathway for transfer of radioiodine, including the development of a prediction model for this transfer. The program was conducted at the Southwestern Radiological Health Laboratory† because of its proximity to the Nevada Test Site and the desire to do field experiments, with all their concomitant problems, during planned releases of radioactive materials and thus obtain realistic data.

Concurrent with the field experiments, a series of controlled experiments was conducted in which aerosols of known characteristics were used to contaminate various types of dairy cow forage with iodine-131. The controlled experiments were conducted at a dairy farm managed by the Laboratory (Douglas 1967, Smith and Engel 1969) located in Area 15 on the Nevada Test Site.

A resumé of the experiments conducted since this program started is shown in Table 1. Results of these experiments were used to evaluate many of the factors involved in constructing a prediction model for the transfer of radioiodine to man through the forage-cow-milk route. The factors considered in designing these experiments included:

- Those affecting uptake by the cows
  - mode of exposure (inhalation, ingestion)
  - type of food (hay, fresh forage)
  - arrangement of feed (spread or baled hay, chopped or growing forage)
  - species of forage (Sudan grass, alfalfa, oats, barley)
  - physical form of contaminant (gaseous, particulate)
  - chemical form of contaminant (iodine, iodate, organic, etc.)
  - biological availability (prepared aerosols, effluent from various nuclear tests)

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* Since January 1975 the U.S. Energy Research and Development Administration

† In December 1970, this PHS Laboratory became a part of the newly formed U.S. Environmental Protection Agency (EPA) and was later renamed the Environmental Monitoring and Support Laboratory-Las Vegas.

TABLE 1. RADIOIODINE EXPERIMENTS

| *Release Type:* Name & Date of Experiment | Cows Per Group | Type of Exposure | Type of Forage | Species of Forage | Remarks |
|---|---|---|---|---|---|
| *Controlled Releases:* | | | | | |
| Milkrun 8-11-65 (Shimoda et al., 1970) | 8 | Single oral | | | Used NaI with $^{126}I$ and $^{131}I$ |
| Hayseed 10-4-65 (Barth and Seal 1966) | 4 | Inhalation | Uncontaminated | | Used diatomaceous earth-$^{131}I$ dry aerosol, 23-μm count median diameter (CMD) |
| | 4 | Ingestion | Spread hay | Alfalfa | |
| | 4 | " | Spread green chop | Sudan | |
| | 4 | " | Green chop | " | |
| Alfalfa 6-21-66 (Stanley et al., 1969) | 4 | Inhalation | Uncontaminated | | Used diatomaceous earth-$^{131}I$ dry aerosol, 2-μm CMD |
| | 4 | Ingestion | Spread hay | Alfalfa | |
| | 4 | " | Spread green chop | Alfalfa-oats | |
| | 4 | " | Green chop | " | |
| Rainout 9-29-66 (Douglas et al., 1971) | 6 | Ingestion | Spread hay | Alfalfa | Used water spray with $Na^{131}I$, 169-μm droplets |
| | 6 | " | Green chop | " | |
| SIP 6-6-67 (Mason et al., 1971) | 6 | Inhalation | Uncontaminated | | Used diatomaceous earth-$^{131}I$ dry aerosol, 0.13-μm CMD |
| | 6 | Inhalation plus ingestion | Hay | Alfalfa | Hay in manger during contamination |
| | 6 | | Green chop | " | |
| MICE 9-21-67 (Black et al., to be published) | 6 | Inhalation | Uncontaminated | | Gaseous $^{131}I_2$ |
| | 6 | Ingestion | Hay | Alfalfa | Inhalation + baled hay + hay made from pasture |
| | 6 | " | Green chop | " | |

(Continued next page)

TABLE 1. RADIOIODINE EXPERIMENTS — Continued

| *Release Type:* Name & Date of Experiment | Cows Per Group | Type of Exposure | Type of Forage | Species of Forage | Remarks |
|---|---|---|---|---|---|
| HARE 9-18-68 (Black et al., 1975) | 3 | Ingestion | Green chop | Sudan | Used diatomaceous earth-$^{131}I$ dry aerosol, 0.6-μm CMD |
| | 3 | " | " | Alfalfa | |
| *Accidental Releases, using commercial dairies:* | | | | | |
| Pike 3-13-64 (Barth and Veater 1964) | 3 | Ingestion | Green chop | Alfalfa-barley | Balance of herd on baled hay; pasture feed started 5 days after event |
| | 3 | " | " | " | |
| Pin Stripe 4-25-66 (Barth et al., 1969) | 4 | Ingestion | Green chop | Alfalfa | Balance of herd on hay |
| | 6 | " | Green chop + hay | " | Fed green chop or hay intermittently |
| *Planned Releases*:* | | | | | |
| TNT 1-12-65 (Black et al., 1969) | 5 | Ingestion | Spread hay | Alfalfa | Planned destruction of a rocket reactor |
| | 5 | " | " | " | |
| Palanquin 4-14-65 (Black et al., 1971a) | 4 | Inhalation | Uncontaminated | | |
| | 6 | Ingestion | Spread hay | Alfalfa | Forage from location where inhalation cows were placed |
| | 6 | " | Spread green chop | " | |
| | 3 | " | Spread hay | " | Hay from different location |
| | 3 | Inhalation | Uncontaminated | | Sacrificed for tissue distribution |
| Cabriolet 1-26-68 (Black et al., 1971b) | 4 | Ingestion | Baled hay | Alfalfa | Only one station contaminated |

(Continued next page)

* Other experiments were planned for Tory, Kiwi, NRX and NRX-A6 reactor runs and the Sulky cratering event, but the amounts of radioactivity released were too small.

TABLE 1. RADIOIODINE EXPERIMENTS — Continued

| *Release Type:* Name & Date of Experiment | Cows Per Group | Type of Exposure | Type of Forage | Species of Forage | Remarks |
|---|---|---|---|---|---|
| Buggy 3-12-68 (Black et al., 1971b) | 4 | Ingestion | Baled hay | Alfalfa | Fed for 8 days (Station 2) |
| | 4 | " | " | " | Single feeding (Station 2) |
| | 4 | " | " | " | Fed for 8 days (Station 4) |
| | 4 | " | " | " | Single feeding (Station 4) |
| Schooner 12-6-68 (Black et al., 1972) | 4 | Ingestion | Baled hay | Alfalfa | Each group fed hay contaminated at a different location |
| | 4 | " | " | " | |
| | 4 | " | " | " | |

- Those affecting transfer to milk
  - variation among cows (percent secretion in milk)
  - stable iodine intake
  - thyroid status
  - stage of lactation
  - single versus multiple intake

Inhalation exposure is referred to as air uptake in this paper because concurrent ingestion generally occurs when the cow licks its muzzle, nares, or surrounding objects.

In many experiments, a deliberate effort was made to obtain high levels of contamination. For example, when contaminating hay for feeding experiments, the hay was unbaled and spread out on plastic sheets to allow maximum deposition of activity. For fresh forage feeding, the contaminated forage was cut fresh daily (green chop) and fed rather than allowing the cows to graze. Feeding green chop (dry-lot feeding practice) is the most common procedure used by dairies in the Great Basin area. The forage plot at the dairy farm had an average yield, for this period, of about 1.5 kilograms fresh weight per square meter. The cows' stable iodine intake was approximately 250 milligrams per day estimated from periodic measurements of feed. To insure a realistic herd average, cows in all stages of lactation as well as high and low producers were used in the experimental groups. Thus a given experimental group might have cows in which only 2 to 3 percent of the ingested radioiodine was transferred to milk during the experimental period as well as cows with transfers of 20 to 30 percent.

Since the amount of forage consumed by the cow will affect some of the measured parameters, all of the results used in this report have been adjusted mathematically by using standard ingestion data, based on the observed feeding habits of the 26-cow dairy herd, and the actual milk secretion curves of the individual cows during each experiment.

The standard ingestion data were: fresh forage -- 24 kilograms per day in two feedings, or high quality hay -- 18 kilograms fresh weight per day in two feedings.

Grain intake for either of the above regimens was 3.5 kilograms at each milking or 7 kilograms per day. The amounts fed were based on the schedules recommended by Morrison (1959). The dairy farm was operated as a Grade A dairy with above-average veterinary care and with meticulous records on each cow. For comparison with other dairy cow studies, the following characteristics of the herd, which consisted of both grade and registered Holsteins, are listed.

| Herd Characteristics | Average | Range |
|---|---|---|
| Number of milking cows | 18 | 16-19 |
| Days in lactation | 271 | 250-310 |
| Milk produced (liters/day) | 21.5 | 18-25 |
| Cow weight (kilograms) | 585 | 530-813 |
| Feces output, 218 samples (kilograms/day) | 34.2 | 21.2-49.2 |
| Urine output, 218 samples (kilograms/day) | 25.7 | 11.6-39.5 |

The results obtained from the experiments listed in Table 1 are shown in Table 2 (physical data) and Table 3 (milk data). These results are the foundation of the prediction procedures which are outlined in subsequent sections of this report. Where appropriate data are available, results from the Off-Site Surveillance Program* conducted by this Laboratory are included. Dashes in the tables indicate that data were not available.

## SUMMARY

Over a 5-year period, 14 major experiments were conducted to investigate the air-forage-cow-milk system for transfer of radioiodine. The experiments included controlled releases using prepared aerosols, planned releases during Plowshare cratering tests, and releases due to accidental venting of underground nuclear tests. Two or more groups of dairy cows, three to six cows per group, were used in each experiment to study the effect on radioiodine transfer of such factors as the mode of exposure, the type and state of forage fed, the type of aerosol, a d variations in feeding practices. In each experiment, measurements were made of the total radioiodine intake and output in milk of the cows, the concentrations in forage and milk, the gaseous and particulate air concentrations, the open-field gamma exposure rate and the deposition per unit area.

The mean values of the experimental data are assembled in this report and are used to develop the parameters for a standard milk excretion pattern for dairy cows and to develop predictive equations for radioiodine. The resultant equations, for predicting the infinite dose to a 2-gram thyroid caused by

* A program conducted for the Nevada Operations Office of the U.S. Energy Research and Development Administration (SWRHL 1970, WERL 1972)

TABLE 2. PHYSICAL DATA FOR RADIOIODINE MODEL

| Name and Date of Experiment | Cows Per Group | Distance (mi.) | Peak γ-dose Rate[1] (mR/h) | Dose Rate @ 6h (mR/h) | Planch.[2] (μCi/m²) | Air[3] (μCi-s/m³) | F/C[4] Ratio | Particle[5] Size (μm) | Peak Forage Concen. (nCi/kg) | $T_{eff}$ in Forage (days) | Days Fed |
|---|---|---|---|---|---|---|---|---|---|---|---|
| *Exposure Route:* | | | | | | | | | | | |
| *Hay:* | | | | | | | | | | | |
| Pike | 3 | 84 | 0.1 | 0.08 | | | | | | | |
| 03/13/64 | 3 | 84 | 0.06 | 0.05 | | | | | 1.3 | | |
| | | | | | | | | | 0.65 | | |
| Palanquin | 6 | 2.85 | $2x10^4$ | 2,300 | 206 | 264 | 3.4 | | 26,000 | | 8 |
| 04/14/65 | 3 | 3.5 | 17 | 2 | 1.5 | 3.5 | 0.11 | | 385 | | 24 |
| TNT | 5 | 1.5 | 9.0 | 1.05 | | ND | | | | | |
| 01/12/65 | 5 | 0.75 | 2.9 | 0.34 | | ND | | | 5.1 | 2.4 | 6 |
| | | | | | | | | | 1.6 | 4.0 | 6 |
| Cabriolet 01/26/68 | 4 | 2.8 | 31 | 3 | 1.04 | 9.92 | 1.43 | | 68.4 | 6.2 | 8 |
| Buggy | 4 | 10 | 252 | 25 | 18.2 | 52 | 14.6 | 0.6 | 452 | | |
| 03/12/68 | 4 | 10 | 252 | 25 | 18.2 | 52 | 14.6 | 0.6 | 121 | | 0.5 |
| | 4 | 10 | 64 | 6.2 | 3.1 | 7.9 | 6.6 | 0.6 | 57 | 6.8 | 8 |
| | 4 | 10 | 64 | 6.2 | 3.1 | 7.9 | 6.6 | 0.6 | 20.7 | | 0.5 |
| Schooner | 4 | 46 | 100 | 55 | 6.43 | 3.2 | 6.4 | 0.6-0.9 | 56 | 8.2 | 10 |
| 12/08/68 | 4 | 43.5 | 34 | 30 | 1.93 | 2.0 | 4.1 | 0.6-0.9 | 19 | 10.5 | 10 |
| | 4 | 29 | 14 | 7 | 0.39 | 1.5 | 13.7 | 0.6-0.9 | 4.3 | 7.9 | 10 |
| | | 136 | 0.58 | 0.68 | | | | | | | |
| Hayseed 10/04/65 | 4 | | | | 3.13 | 323 | 4.9 | 23 | 405 | | 6 |
| Alfalfa 06/21/66 | 4 | | | | 4.66 | 333 | 3.5 | 2 | 640 | 6.5 | 8 |
| Rainout 09/29/66 | 6 | | | | 24.6 | 5.6 | 0.33 | 169(drop) | 9,800 | 3.6 | 7.5 |
| SIP 06/06/67 | 6 | | | | 1.63 | 157 | 3.2 | 0.13 | 79.8 | | 0.5 |

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TABLE 2. PHYSICAL DATA FOR RADIOIODINE MODEL — Continued

| *Exposure Route:* Name and Date of Experiment | Cows Per Group | Distance (mi.) | Peak γ-dose Rate[1] (mR/h) | Dose Rate @ 6h (mR/h) | Planch.[2] (μCi/m²) | Air[3] (μCi-s/m³) | F/C[4] Ratio | Particle[5] Size (μm) | Peak Forage Concen. (nCi/kg) | $T_{eff}$ in Forage (days) | Days Fed |
|---|---|---|---|---|---|---|---|---|---|---|---|
| *Hay:* | | | | | | | | | | | |
| MICE | 6 | | | | 0.66 | 132 | 0.12 | gas | 2,110 | 5.9 | 10.5 |
| 09/21/67 | 6 | | | | 0.66 | 132 | 0.12 | gas | 102 | 2.2 | 3 |
| *Green Chop:* | | | | | | | | | | | |
| Pike | 3 | 84 | 0.1 | 0.08 | | | | | 4.7 | 5.3 | |
| 03/13/64 | 3 | 84 | 0.06 | 0.05 | | | | | 1.7 | 5.3 | |
| Palanquin 04/14/65 | 6 | 2.85 | $2x10^4$ | 2,300 | 206 | 264 | 3.4 | | 45,400 | - | 4 |
| Pin Stripe | 4 | 63 | 1.6 | 1.1 | | 21.7 | 3.0 | | 56 | 4.9 | 14 |
| 04/25/66 | 6 | 54 | 0.38 | 0.28 | | 6.6 | 1.9 | | 18 | 4.0 | 14 |
| Hayseed | 4 | | | | 3.13 | 323 | 4.9 | 23 | 1,900 | - | 4 |
| 10/04/65 | 4 | | | | 3.13 | 323 | 4.9 | 23 | 2,700 | 3.6 | 6 |
| Alfalfa | 4 | | | | 4.66 | 334 | 3.5 | 2 | 260 | - | 3 |
| 06/21/66 | 4 | | | | 4.66 | 334 | 3.5 | 2 | 3,400 | 2.1 | 9 |
| Rainout 09/29/66 | 6 | | | | 24.6 | 5.6 | 0.33 | 169(drop) | 21,000 | 4.5 | 8 |
| SIP 06/06/67 | 6 | | | | 1.63 | 157 | 3.2 | 0.13 | 1,130 | 4.1 | 10 |
| MICE 09/21/67 | 6 | | | | 0.66 | 132 | 0.12 | gas | 2,630 | 4.0 | 8 |
| HARE | 3 | | | | 1.25 | 87.5 | 1.0 | 0.6 | 1,030 | 2.4 | 5 |
| 09/18/68 | 3 | | | | 1.43 | | 1.0 | 0.6 | 775 | 3.8 | 5 |
| Milkrun 08/11/65 | 8 | | | | | | | | 118μCi | Capsule | 1 |

(Continued next page)

TABLE 2. PHYSICAL DATA FOR RADIOIODINE MODEL — Continued

| Name and Date of Experiment | Cows Per Group | Distance (mi.) | Peak γ-dose Rate[1] (mR/h) | Dose Rate @ 6h (mR/h) | Planch.[2] (μCi/m²) | Air[3] (μCi-s/m³) | F/C[4] Ratio | Particle[5] Size (μm) | Peak Forage Concen. (nCi/kg) | $T_{eff}$ in Forage (days) | Days Fed |
|---|---|---|---|---|---|---|---|---|---|---|---|
| *Exposure Route:* | | | | | | | | | | | |
| *Air Uptake:* | | | | | | | | | | | |
| Palanquin 04/14/65 | 4 | 2.8 | $2x10^4$ | 2,300 | 206 | 264 | 3.4 | | | | |
| Hayseed 10/04/65 | 4 | | | | 3.13 | 323 | 4.9 | 23 | | | |
| Alfalfa 06/21/66 | 4 | | | | 4.66 | 334 | 3.5 | 2 | | | |
| SIP 06/06/67 | 6 | | | | 1.63 | 157 | 3.2 | 0.13 | | | |
| MICE 09/21/67 | 6 | | | | 0.66 | 132 | 0.12 | gas | | | |

1-γ dose-rate measured 3 feet above ground
2-Deposition on planchets
3-Integrated air concentration
4-Activity on filter divided by activity on charcoal
5-Count median diameter of the aerosol

TABLE 3. MILK DATA FOR RADIOIODINE MODEL

| Exposure Route: Name and Date of Experiment | Peak Milk (nCi/liter) | Percent of Dose in Milk | 1st $T_{eff}$ (days) | 2nd $T_{eff}$ (days) | 3rd $T_{eff}$ (days) | Peak Milk / Peak Forage | Time to Peak (days) | Average Milk Production (liters/day) | Remarks |
|---|---|---|---|---|---|---|---|---|---|
| *Hay:* | | | | | | | | | |
| Pike | 0.07 | - | - | - | - | 0.054 | - | - | Baled hay |
| 03/13/64 | 0.03 | - | - | - | - | 0.046 | - | - | Baled hay |
| Palanquin | 2,260 | 9.6 | 6.2 | 0.94 | 3.12 | 0.087 | 2.5 | 13.9 | Spread hay |
| 04/14/65 | 17.3 | 12.7 | 5.0 | - | - | 0.045 | 4.0 | 16.3 | Spread hay |
| TNT | 0.18 | 7.4 | 5.7 | 1.7 | | 0.035 | 2.0 | 15.5 | Spread hay |
| 01/12/65 | 0.16 | 22.6 | 2.9 | 1.2 | | 0.098 | 2.0 | 16.6 | Spread hay |
| Cabriolet | 0.841 | 2.16 | 11.9 | 1.7 | | 0.012 | 2.0 | 20.1 | Baled hay |
| 01/26/68 | | | | | | | | | |
| Buggy | 3.37 | 1.19 | - | 0.78 | | 0.0074 | 5.6 | 17.8 | Baled hay |
| 03/12/68 | 1.06 | 2.77 | - | 0.61 | | 0.0088 | - | 19.2 | Baled hay, single feeding |
| | 0.66 | 1.36 | - | 0.92 | | 0.011 | 8.0 | 15.1 | Baled hay |
| | 0.14 | - | - | 0.68 | | 0.0069 | - | 18.7 | Baled hay, single feeding |
| Schooner | 1.20 | 3.94 | 63 | 0.75 | | 0.021 | 9.6 | 19.1 | Baled hay |
| 12/08/68 | 0.354 | 2.88 | 30 | 0.68 | | 0.019 | 10.0 | 16.7 | Baled hay |
| | 0.084 | 2.59 | 38 | 0.74 | | 0.020 | 4.6 | 13.7 | Baled hay |
| | 0.063 | | | | | | | | |
| Hayseed | 29.8 | 6.3 | 2.7 | <1 | 3.0 | 0.074 | 1.4 | 20 | Spread hay |
| 10/04/65 | | | | | | | | | |
| Alfalfa | 47.4 | 15.2 | 8.2 | 0.9 | | 0.074 | 0.8 | 21.3 | Spread hay, bagged immediately |
| 06/21/66 | | | | | | | | | |
| Rainout | 196 | 4.5 | 2.5 | 0.9 | 5.6 | 0.02 | 1.1 | 20.4 | Spread hay, $^{131}I$-labeled NaI in water |
| 09/29/66 | | | | | | | | | |
| SIP | 3.15 | - | | 1.05 | | 0.04 | - | 21.9 | Spread hay, single feeding |
| 06/06/67 | | | | | | | | | |

(Continued next page)

TABLE 3. MILK DATA FOR RADIOIODINE MODEL — Continued

| Name and Date of Experiment | Peak Milk (nCi/liter) | Percent of Dose in Milk | 1st $T_{eff}$ (days) | 2nd $T_{eff}$ (days) | 3rd $T_{eff}$ (days) | Peak Milk / Peak Forage | Time to Peak (days) | Average Milk Production (liters/day) | Remarks |
|---|---|---|---|---|---|---|---|---|---|
| *Exposure Route:* | | | | | | | | | |
| *Hay:* | | | | | | | | | |
| MICE 09/21/67 | 137 | 11.5 | 4.5 | 0.75 | 2.8 | 0.065 | 3.7 | 19.2 | Hay baled from contaminated pasture. (Considered same as green chop) |
| | 17.8 | - | 1.1 | - | | 0.174 | - | 19.2 | Inhalation + baled hay |
| *Green Chop:* | | | | | | | | | |
| Pike 03/13/64 | 0.42 | - | 3.8 | - | - | 0.089 | - | 10.5 | Jersey cows, 1 feeding/day alfalfa-barley green chop |
| | 0.07 | - | 4.0 | - | - | 0.041 | - | 5.8 | |
| Palanquin 04/14/65 | 2,700 | 5.6 | 16.0 | 1.05 | 3.3 | 0.060 | 3.0 | 16.0 | |
| Pin Stripe 04/25/66 | 4.8 | 10.4 | 5.6 | 1.0 | - | 0.086 | 2.0 | 20.1 | |
| | 1.4 | 4.9 | 4.0 | - | - | 0.078 | 3.0 | 16.7 | |
| Hayseed 10/04/65 | 38.5 | 2.0 | 2.3 | <1 | - | 0.020 | 2.0 | 24.5 | Sudan, spread green chop |
| | 75.8 | 2.1 | 3.0 | <1 | 3.0 | 0.028 | 2.4 | 21.0 | Sudan, fresh green chop |
| Alfalfa 06/21/66 | 26.2 | 14.8 | - | 1.5 | | 0.10 | 2.0 | 28.1 | Alfalfa-oats, spread green chop |
| | 237 | 12.5 | 2.5 | 0.9 | | 0.07 | 1.2 | 23.6 | Alfalfa-oats, fresh green chop |
| Rainout 09/29/66 | 1,572 | 6.1 | 7.9 | 0.86 | 5.1 | 0.075 | 1.7 | 17.8 | Alfalfa, fresh green chop |
| SIP 06/06/67 | 68.4 | 7.6 | 5.2 | 1.2 | 3.2 | 0.061 | 1.6 | 22.5 | Alfalfa, fresh green chop |

(Continued next page)

TABLE 3. MILK DATA FOR RADIOIODINE MODEL — Continued

| Name and Date of Experiment | Peak Milk (nCi/liter) | Percent of Dose in Milk | 1st $T_{eff}$ (days) | 2nd $T_{eff}$ (days) | 3rd $T_{eff}$ (days) | Peak Milk / Peak Forage | Time to Peak (days) | Average Milk Production (liters/day) | Remarks |
|---|---|---|---|---|---|---|---|---|---|
| *Exposure Route:* | | | | | | | | | |
| *Green Chop:* | | | | | | | | | |
| MICE 09/21/67 | 151 | 8.5 | 7.1 | 0.74 | 3.9 | 0.058 | 2.0 | 19.4 | Alfalfa, fresh green chop |
| HARE 09/18/68 | 21.6 | 3.6 | 4.5 | 0.85 | 3.7 | 0.021 | 2.0 | 25.1 | Sudan, fresh green chop |
| | 50.8 | 7.2 | | 0.74 | 3.8 | 0.066 | 4.0 | 23.4 | Alfalfa, fresh green chop |
| Milkrun 08/11/65 | 500 | 8.6 | | 0.61 | | | 0.2 | 23.1 | Given single capsule containing $^{131}I + ^{126}I$ |
| *Air Uptake:* | | | | | | | | | |
| Palanquin 04/14/65 | 1,200 | - | - | 1.3 | - | - | 2.25 | 17.6 | Evidence of some ingestion |
| Hayseed 10/04/65 | 0.58 | - | - | 0.8 | - | - | 0.4 | 21.0 | |
| Alfalfa 06/21/66 | 2.2 | - | - | 0.9 | - | - | 0.9 | 25.8 | |
| SIP 06/06/67 | 1.17 | - | - | 1.1 | - | - | 1.6 | 20.1 | |
| MICE 09/21/67 | 3.6 | - | - | 0.8 | 2.81 | - | 0.7 | 21.9 | |

ingestion of iodine-131, are divided into two major categories, post-event and pre-event, and are estimated to be accurate to a factor of 2 or less. The equations are:

Post-event predictions

For cows on hay

$$D_\infty = 0.042(mR/h) \quad (1)$$

$$D_\infty = 0.014(IAC) \quad (2)$$

For cows on fresh forage

$$D_\infty = 0.37(mR/h) \quad (3)$$

$$D_\infty = 0.072\left(\frac{IAC}{F/C}\right) \quad (4)$$

Pre-event predictions

For cows on fresh forage

$$D_\infty = 1500(kt)(S)^{-1.32} \quad (5)$$

For cows on hay

$$D_\infty = 176(kt)(S)^{-1.32} \quad (6)$$

where $D_\infty$ = infinite dose in rads
mR/h = peak gamma exposure rate, or the H+6 hour rate (extrapolated backward) if the peak occurs later than H+6 hours
IAC = integrated air concentration in curies times seconds per square meter ( Ci-s/m )
F/C = iodine-131 activity on the filter divided by that on charcoal
kt = fission yield in kilotons vented to the atmosphere
S = distance from surface ground-zero in miles

If the fresh forage is Sudan grass, then the results from equations 3, 4 and 5 may be divided by 3. Equations 5 and 6 apply if no concentrating effect occurs (rainout, etc.). If a concentrating effect is present, it is suggested that the results be increased by a factor of 10.

Comparison of the results obtained by use of the above equations with the results obtained by other authors indicated good agreement among them. However, the data in this report permit a better prediction by including corrections for the type and state of the cow forage, and by including equations for pre-event predictions.

Data on the short-lived radioiodines (the 132, 133, and 135 isotopes) were collected in several studies. These isotopes, in fresh fallout, increase the dose to a 2-gram thyroid by 38 percent if cows are ingesting contaminated fresh forage and by 12 percent if ingesting contaminated hay. The dose delivered by these radioiodines would be decreased by 90 percent if the milk consumption were to be delayed for 4 days after the nuclear event. Inhalation of activity during cloud passage (passage of the airborne effluent) could increase the dose to an infant by a maximum of 6 percent if the cows were on fresh feed and 30 percent if the cows were on hay.

A test of the equations developed herein, using data collected following the accidental venting of the Baneberry event*, indicated that a reasonably accurate prediction of peak iodine-131 concentration in milk was possible.

## CHEMICAL AND PHYSICAL FORM

The predominant physical forms of iodine in air are the gaseous and particulate forms, and their ratio can vary widely. This ratio has some effect on deposition and will be discussed later in this report. The particulate forms include iodides and iodates, among others, some of which were bound to particles at the time of formation and others which were adsorbed on particles at later times. The gaseous forms include $I_2$, HI and organic iodides. The relative proportions of the gaseous forms have not been measured under field conditions. However, only the organic forms vary drastically in deposition (Bunch 1968) and these are minor constituents of fallout clouds.

It would appear that the chemical form of the iodine might affect its metabolism. However, the literature contains reports of studies with iodates in grazing animals and with methyl iodide ($CH_3I$) in man which suggest that chemical form is unimportant. To investigate this more fully, a study of milk secretion of iodine-131 in diary cows following ingestion of four different chemical compounds was conducted (Bretthauer et al., 1962). The results indicate no difference for iodine secretion in milk following oral administration of sodium iodide (NaI), gaseous iodine ($I_2$), methyl iodide ($CH_3I$) or sodium iodate ($NaIO_3$).

It would thus be possible to ignore chemical or physical form in the studies reported here with the proviso that if organic iodides are ever present as the predominant chemical form in a fallout situation, then deposition and the resultant forage-cow-milk transfer will be less than those calculated in this report.

## MILK SECRETION PARAMETERS

The milk secretion of radioiodine, following multiple ingestion of forage contaminated by a single event, follows a general pattern as shown in the semi log plot, Figure 1. The concentration of the radionuclide in milk first increases to a peak value, then apparently decreases biphasically, unless the duration of intake is short; then a component ($T_2$) appears more prominently as shown in the figure.

This $T_2$ component appears when the supply of contaminated feed is short (10 to 12 days or less) or when uncontaminated feed is substituted for contaminated feed as a countermeasure, as was done in the Pin Stripe event (Barth et al., 1969).

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* Baneberry was an underground nuclear test of less than 20 kilotons yield conducted at the Nevada Test Site on December 18, 1970.

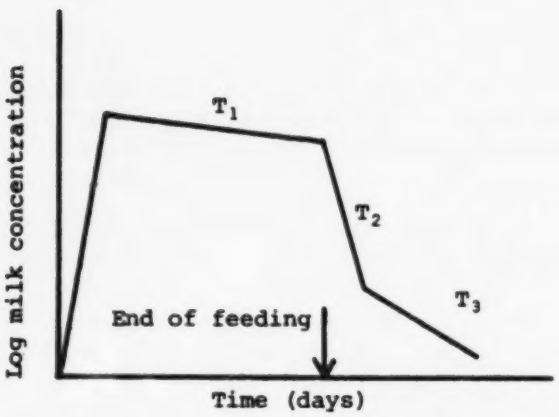


Figure 1. General pattern of iodine-131 secretion in milk following ingestion

The values for the various portions of the curve in Figure 1 plus other measured parameters are shown in Table 4. These data suggest little difference between spread hay or fresh pasture as contaminated forage relative to the transfer of radioiodine to cow's milk. The principal difference is in the amount of activity that accumulates on the two types of forage. When exposed to the same radioactive cloud, the concentration in growing pasture (microcuries per kilogram fresh weight) is five to six times the concentration attained in spread hay.

TABLE 4. MEASURED PARAMETERS FOR RADIOIODINE TRANSFER TO MILK (Mean ± Standard Error)

| Parameter | Cows Fed Green Chop (9)* | Cows Fed Spread Hay (8) | Cows Fed Baled Hay (7) | Air Uptake Exposure (4) |
|---|---|---|---|---|
| Time of peak (days)† | 2.2 ± 0.2 | 2.2 ± 0.4 | 4.2 ± 1.0 | 0.6 ± 0.2 |
| $T_1$ (effective $T_{\frac{1}{2}}$ in days)† | 4.7 ± 0.5 | 4.2 ± 0.7 | 36 ± 10‡ | 0.9 ± 0.1 |
| $T_2$ (effective $T_{\frac{1}{2}}$ in days)† | 0.97 ± 0.07 | 1.0 ± 0.1 | 0.8 ± 0.08 | |
| $T_3$ (effective $T_{\frac{1}{2}}$ in days)† | 3.7 ± 0.3 | 3.6 ± 0.7 | | |
| $T_{eff}$ on forage (days) | 4.2 | 6.5 | 6.6§ | |
| Peak conc. in milk ÷ peak conc. in forage | 0.068 | 0.069 | 0.024 | |
| Secretion in milk (%) | 8.9 ± 1.3 | 8.5 ± 1.5 | 2.4 ± 0.4 | |

* The number of experiments averaged. Each experiment was an average for three to six cows.

† These parameters are labeled in Figure 1.

‡ This value is an artifact caused by uneven distribution of activity in the hay as fed to the cows. The $T_{eff}$ cannot be longer than the 8.05-day half-life of iodine-131.

§ The total hay for the three Schooner groups was chopped and stored in an enclosure. The data were not used for this $T_{eff}$.

The data for the groups of cows fed baled hay (Table 4) are based on experiments conducted during three cratering events (Cabriolet, Buggy and Schooner). They show a striking difference from the other feeding regimens in that the percent of iodine-131 secreted in milk is 2 to 2.8 percent for cows fed baled hay as compared to 7 to 10 percent for the other cases. This is probably due

to the chemical or physical state of the debris released by these Plowshare* events which apparently caused the radioiodines to be less biologically available.

Air uptake represents a relatively minor mode of exposure for dairy cows. In four experiments where air uptake and ingestion were compared, the peak radioiodine concentration in milk following multiple ingestion (using maximum values) was 22 to 110 times the peak concentration following air uptake. Further, the continued ingestion of contaminated forage, following a single deposition of radioactivity, would accentuate this difference in exposure.

Some calculations using the air uptake data are shown in Table 5, These calculations assume approximately 100 liters per minute as the respiratory rate for the cow (Altman and Dittmer 1964) and they assume that this minute volume times the integrated air concentration (IAC) gives the cow exposure. The relatively high percent of the calculated exposure which is secreted in the milk suggests that inhalation was not the sole method of intake in these experiments.

TABLE 5. INHALATION EXPOSURE CALCULATIONS

| Value No. | Calculated Value | Hayseed | Alfalfa | Sip | Mice |
|---|---|---|---|---|---|
| 1 | Integrated Air Concentration ($\mu Ci\text{-}s/m^3$) | 323 | 334 | 157 | 132 |
| 2 | Minute volume ($m^3/s$) | 0.0017 | 0.0017 | 0.0017 | 0.0017 |
| 3 | [1×2] Total exposure (nCi) | 550 | 570 | 270 | 220 |
| 4 | Peak milk conc. (nCi/liter) | 0.58 | 2.2 | 1.17 | 3.6 |
| 5 | [4÷3] % in milk at peak | 0.11 | 0.39 | 0.43 | 1.64 |
| 6 | Total in milk (nCi) | 13.4 | 190 | 54 | 177 |
| 7 | [6÷3] Total as % exposure | 2.4 | 33 | 20 | 80 |
| 8 | Particle size ($\mu m$) | 23 | 2 | 0.13 | Gas |

The data from Tables 2 and 3 can be used to develop predictive models for nuclear tests or accidents but, for maximum utility, such a prediction also requires an estimate of the amount or percentage of radioactive materials which may be released to the atmosphere. Ignoring this for the moment, a post-event estimate of the peak radioiodine concentration in milk can be made rather quickly with certain monitoring techniques, as described below. Once the estimate of peak concentration is made, the parameters from Table 4 can be used to estimate the time-course of radioiodine concentration in milk. With these data,

* Plowshare is the U.S. Energy Research and Development Administration program for developing peaceful uses of nuclear explosives.

and assuming an average milk consumption and thyroid uptake, an estimate of human thyroid dose can be made as shown later in this report.

The earliest measurement that can be taken of a contaminated area is the 1-meter gamma exposure rate in milliroentgens per hour (mR/h), usually made with Geiger-Mueller beta-gamma survey meters. Next in time is the integrated air exposure measured by air sampling equipment. Obtainable concurrently, but subject to large sampling error, is the concentration of radioiodine in vegetation.

## SURVEY-METER PREDICTION

This prediction of estimated radioiodine levels in milk can be made quickly, using survey-meter measurements, but it is fraught with errors. The relationship of iodine-131 deposited to the total gamma activity deposited changes with time because of the mixture of decay rates present in the radioactive material deposited. This mixture varies with fractionation in the cloud and with the fusion to fission ratio of the nuclear explosive device. The deposition in a given area can be highly variable because of micrometeorology, the presence of structures, and the terrain. Furthermore, the survey-meter measurement must be made in the immediate area of interest, as the measurement can change drastically with distance.

From the data in Tables 2 and 3, log-log plots were made of the 1-meter gamma exposure rate versus peak milk activity. The exposure rate (mR/h) values used in the graphs included peak measured values, estimated peak values, H+24* extrapolated or measured values, and H+6 extrapolated or peak values. The best relationship was obtained when the peak exposure rate (or mR/h at H+6 if the peak occured later) was plotted against peak milk concentration, as shown in Figures 2 and 3. The H+6 value was determined by extrapolating back from measured values using observed decay data, where possible, or by use of the $t^{-1.2}$ function. The peak exposure rate at a location usually occurs during cloud passage so some "shine†" is measured, but this becomes less important with distance. Also shown in these figures are data from the Off-Site Surveillance Program‡. The data for cows fed green chop compare favorably with ours (Figure 2); however, the off-site data for cows fed hay differ greatly, the peak milk concentration being about 100 times that derived from our data. The dashed lines on each side of the best-fit line are a factor of 2 deviation from that line.

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* H+24: notation meaning 24 hours after detonation; H+6 denotes 6 hours after detonation; D+2 denotes 2 days after detonation; etc.

† "Shine" is radiation measured from radioactivity at a distance rather than from radioactivity close to the measuring instrument or that in which the instrument is immersed. Shine would not be a measure of inhalation exposure or deposition.

‡ A program conducted by the EPA's Environmental Monitoring and Support Laboratory-Las Vegas for the U.S. Energy Research and Development Administration. It monitors radioactive contamination off the Nevada Test Site as described in periodic reports available through the National Technical Information Service.

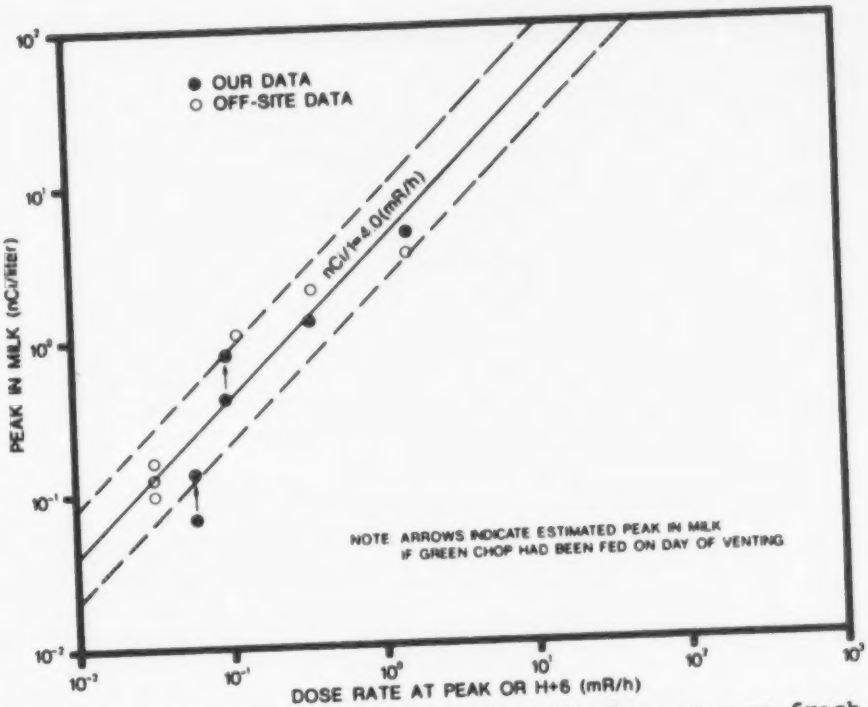
OUR DATA
OFF-SITE DATA
nCi/l=4.0(mR/h)
NOTE ARROWS INDICATE ESTIMATED PEAK IN MILK
IF GREEN CHOP HAD BEEN FED ON DAY OF VENTING
PEAK IN MILK (nCi/liter)
DOSE RATE AT PEAK OR H+6 (mR/h)

Figure 2. Peak iodine-131 concentration in milk from cows on fresh feed versus open-field gamma exposure rate

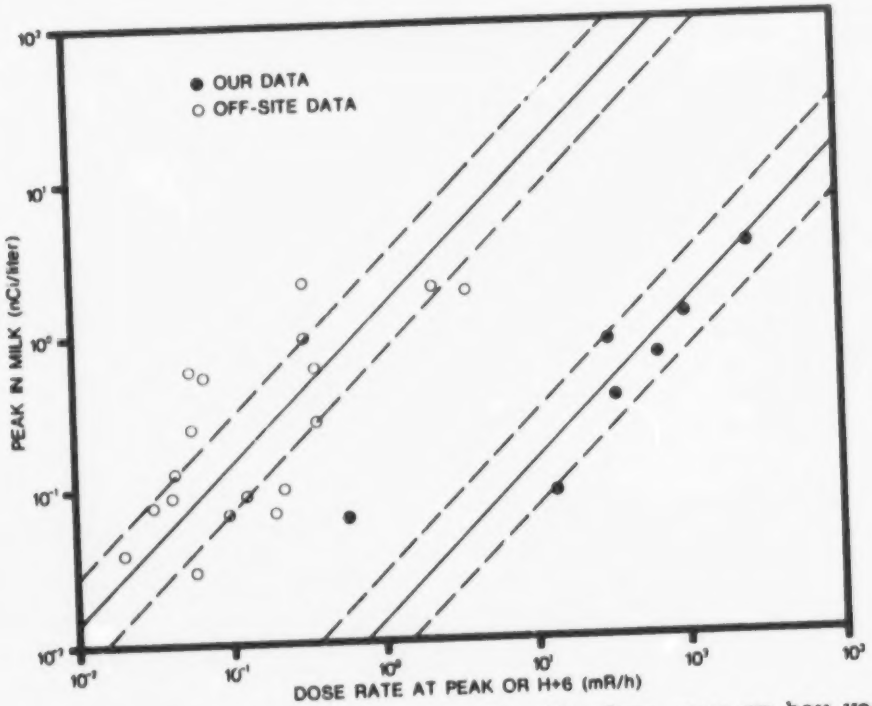


Figure 3. Peak iodine-131 concentration in milk from cows on hay versus open-field gamma exposure rate

From these figures, the equations for estimating the peak milk concentrations from 1-meter gamma exposure rate measurements are:

for cows on fresh feed —

$$\text{nCi/liter} = 4.0(\text{mR/h}) \tag{7}$$

for cows on hay —

using off-site data $$\text{nCi/liter} = 1.4(\text{mR/h}) \tag{8}$$

using our data $$\text{nCi/liter} = 0.014(\text{mR/h}) \tag{9}$$

For cows on fresh feed or hay, then, this very convenient method for estimating the contamination can be used with equation (7) or (9) to predict the peak iodine-131 concentration in milk within a factor of 2.

The great difference between the two sets of data for hay-fed cows is difficult to explain completely, but there are several factors which may contribute to it. The majority of the data are based on survey-meter readings of less than 0.1 mR/h where the accuracy is very poor, and most of the readings were taken near roads where the vegetation may have been less dense than on the farms. Furthermore, most readings were taken in the area of, rather than at, the locations where milk was collected.

Also, our data were obtained from the cratering tests (Cabriolet, Buggy, and Schooner). The activation products in the fallout from Schooner would increase the exposure rate (mR/h) without a concomitant increase in radioiodine. For the other two tests, the experimental stations were so close to the crater (3.2 to 16 kilometers) that larger particles, which would not stick to the hay, would contribute to the exposure rate but not to the radioiodine in milk.

Because the data for green chop are relatively good, it is possible to derive an appropriate equation for cows fed hay. As mentioned in the discussion of milk secretion parameters, the peak concentration in growing pasture is 5 to 6 times the peak attained in spread hay exposed to the same cloud. Also, the milk-to-forage ratios differ by a factor of 2.9 (0.07 for green chop and 0.024 for hay). Thus, the peak concentration in milk from cows on fresh feed should be about 14 times the peak value for cows on hay. Therefore, a reasonable estimate of the peak milk concentration for cows on hay can be obtained by dividing equation (7) by 14.

$$\text{nCi/liter} = \frac{4.0}{14}(\text{mR/h})$$

$$= 0.29(\text{mR/h}) \tag{10}$$

This factor of 14 can be partially substantiated with data from the Palaquin report (Southwestern Radiological Health Laboratory 1970). Of the dairies located in the areas of maximum deposition, there were three using pasture and three using hay, all located about 208 kilometers downwind. The average peak milk concentration was about 8 times higher for cows on pasture. At 480 to 510 kilometers (300 to 325 miles) downwind, the average peak milk concentration at 5 locations using pasture was about 10 times that from cows at 12 locations using hay.

## AIR SAMPLER PREDICTION

After cloud passage, if an air sampler has been operating in the area, the peak iodine-131 concentration in milk in that vicinity can be estimated by use of the integrated air concentration (IAC). This is obtained by adding the iodine-131 activity on the prefilter to that collected on charcoal and dividing the sum by the sampling rate in cubic meters per second ($m^3$/sec). The IAC has the dimensions of curie-seconds per cubic meter (Ci-sec/$m^3$).

The estimate of peak milk concentration again depends on the proximity of the air sampler to the dairy farm, the ratio of gaseous to particulate iodine, and other factors. Since iodine can be determined by gamma spectrometry, the data should be better for our purposes than the data obtained by use of gamma survey meters. The data on IAC versus peak iodine concentration in milk for cows on fresh feed are plotted on log-log coordinates in Figure 4. The best-fit line and factor-of-2 deviation lines are also shown in the figure. The equation for the line is $nCi/liter = 0.17(IAC)^{1.25}$ suggesting a greater than linear increase in milk concentration with IAC.

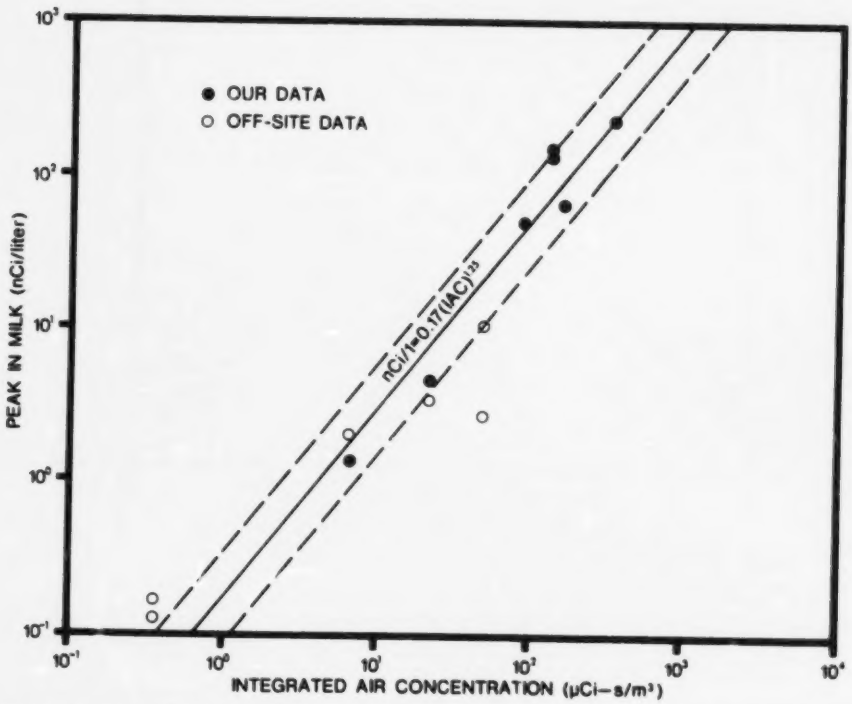


Figure 4. Peak iodine-131 concentration in milk from cows on fresh feed versus integrated concentration of iodine-131 in air

To explain this, it had been noted in earlier experiments that the gaseous to particulate iodine ratio in the contaminating cloud had some effect on the forage-cow-milk transfer (Barth et al. 1969). This may be due to the variation in deposition velocity ($V_g$) between the two species, since $V_g$ for gaseous iodine is much less than 1 centimeter per second, while for particulate iodine it is 1 or larger, occasionally reaching tens or hundreds.

Consequently, for those cases where the data were available, the iodine-131 activity on the prefilter was divided by that on the charcoal cartridge of the air sampler to obtain a filter-to-charcoal ratio (F/C). The F/C is assumed to correlate with the particulate-to-gaseous iodine makeup of the cloud and is therefore used to adjust the IAC data. The revised data are plotted in Figure 5. The best-fit line is now a linear fit to the data (exponent of IAC is 1).

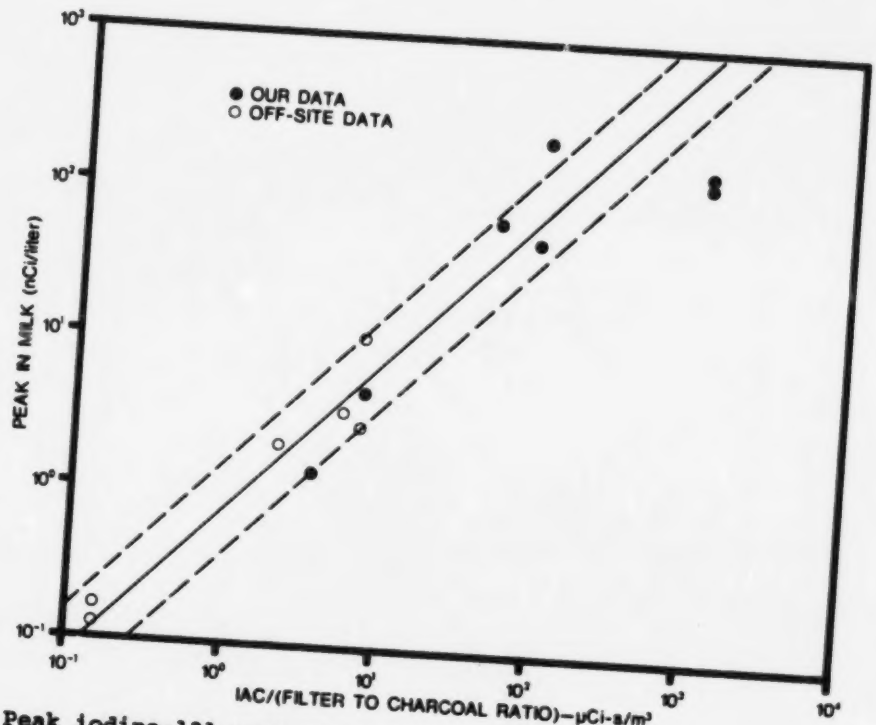


Figure 5. Peak iodine-131 concentration in milk from cows on fresh feed (IAC corrected by the filter-to-charcoal ratio)

This revised plot appears logical, as one would expect the peak concentration of iodine-131 in milk to vary directly with the integrated air concentration of iodine-131. Two of the points in Figure 5, representing the group average data from a gaseous iodine experiment (MICE, Tables 1 through 3) suggest that the F/C correction does not apply for a gaseous aerosol. One could also

postulate a failure of this correction at the other extreme, i.e., iodine on particles too large to be picked up by the air sampler but which would easily be ingested by the cow.

Using air sampler data, then, an estimate of peak milk concentration for cows on fresh forage can be made by use of:

$$\text{peak nCi/liter} = 0.8\left(\frac{IAC}{F/C}\right) \qquad (11)$$

Similar data for cows on hay are shown in Figure 6. In this circumstance the correction for the filter-to-charcoal ratio (F/C) did not improve the fit, perhaps because hay is more like an inert collector than is fresh forage. The equation for the line is:

$$\text{peak nCi/liter} = 0.1(IAC) \qquad (12)$$

The coefficient, compared to Equation 10, indicates the peak concentration in milk from feeding hay is one-eighth of that from feeding fresh forage rather than the one-fourteenth calculated for the survey meter prediction (page 18). The difference is probably due to the inaccuracies in the hay data and to the use of the F/C correction factor.

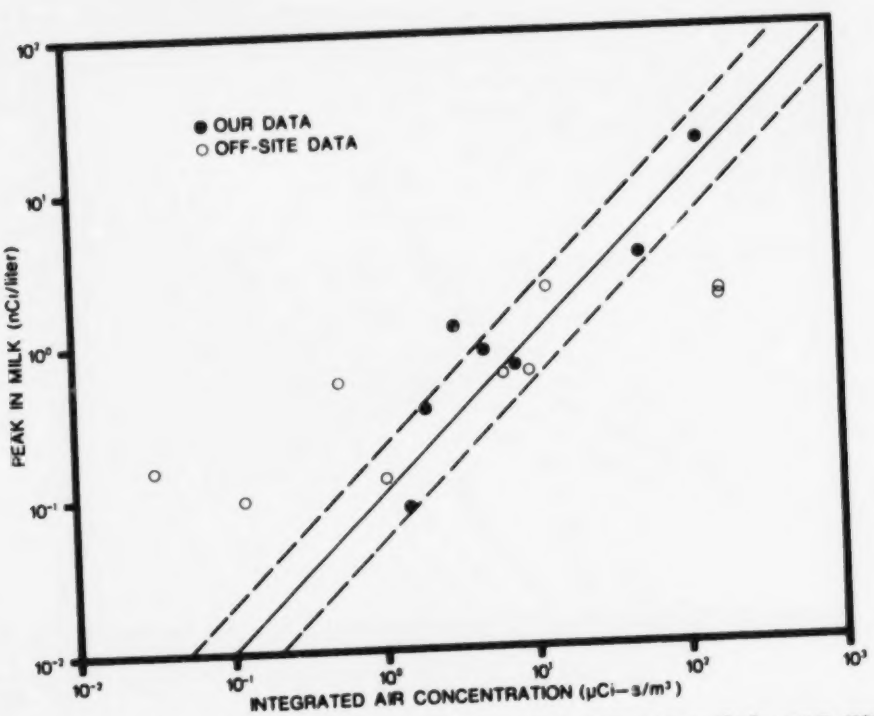


Figure 6. Peak iodine-131 concentration in milk from hay-fed cows versus integrated concentration of iodine-131 in air

## FORAGE PREDICTION

Another relatively quick method of estimating the peak milk concentration is by a measurement of iodine-131 concentration in forage. This measurement, together with the milk-to-forage ratios from Table 4, yield the following estimates:

for fresh forage or spread hay —

$$\text{peak nCi/liter} = 0.07(\text{nCi/kg}) \qquad (13)$$

for baled hay —

$$\text{peak nCi/liter} = 0.024(\text{nCi/kg}) \qquad (14)$$

The equations for predicting the peak milk concentrations for cows on fresh feed apply if the pasture consists of alfalfa, oats, or barley, or a mixture of these. If the fresh feed is Sudan grass, however, the peak will be about one-third the value obtained with the equations. Supporting evidence for the latter was published in 1972 (Moss et al. 1972).

The principal difficulty with forage concentration measurements is in obtaining a representative sample. Baled hay presents an especially difficult problem. The majority of the data in Figure 6 are based on use of upper outside bales of hay from stacks and thus yields a maximum estimate for this type of feeding. Hay spread on the ground or in open troughs would have a higher contamination, while bales in the interior of a stack would be less contaminated.

## PRE-EVENT PREDICTION

This type of prediction was left until last because of the many uncertainties connected with a given event. These include the ratio of fission yield to total yield, the released fraction of fission activity, the degree of fractionation, and unpredictable concentrating factors such as rainout or washout.

Starting with the Palanquin event, the maximum observed iodine-131 concentrations in milk were tabulated with the distance from surface ground zero (SGZ) for each event. Assuming these maximum values were on or near the path of maximum fallout, it should be possible to correlate peak milk concentration with distance. All the milk values were normalized by dividing them by the announced total yield of the event. The log-log plot of the results is shown in Figure 7. The line fit to the five values from Palanquin can be described by Equation 14.

$$\mu\text{Ci/liter-kt} = 2.3(S)^{-1.32} \qquad (15)$$

where S = miles (1 mile = 1.609 kilometers) from surface ground zero

A parallel line, shown as a dashed line, appears to fit some of the data from other field events.

The wide scatter of the points can be reduced by use of two obvious

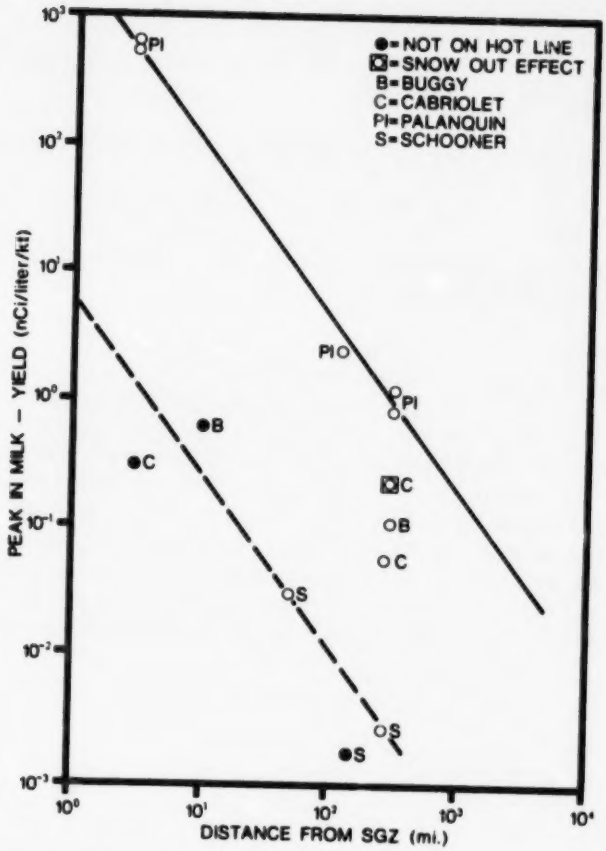


Figure 7. Peak iodine-131 concentration in milk versus distance from surface ground zero (normalized for yield)

corrections. The first correction is to standardize the type of feed through use of the factor of 14, calculated previously, to correct hay data to fresh forage data. The second correction is for the fraction of the activity actually released. This is most easily done by using estimates of the cloud burden of iodine-131 in curies and converting to kilotons of fission by use of the factor $1.25 \times 10^5$ curies per kiloton (iodine-131 from uranium-235 fission). For the Schooner event, the peak milk concentration in nanocuries per liter (nCi/liter) corrected for fresh feed is $1.20 \times 14$, which equals 16.8, and the cloud burden — assuming the iodine-131-to-tungsten-181 ratio is 0.16 and using the upper estimate of total tungsten-181 in the cloud as reported by Anspaugh et al. (1969) — is calculated to have been 0.133 kilotons. Thus, the normalized value, in nCi/liter-kt, becomes $16.8 \div 0.133$, which equals 126.

For lack of cloud burden data for the other cratering tests, assume the same fractional release applies. Thus, the two "hot-line" stations for Schooner, at 74 and 402 kilometers (46 and 250 miles) from surface ground zero, can be used to locate the line for which the slope was set by the Palanquin data which were only assumed to be on the "hot-line." For the underground ventings (Pike and Pin Stripe) the published data on the total activity which escaped (Allen 1971) can be related to kilotons of fission, although probably only the volatile fraction escaped, leading to normalized data which are too high. The raw and corrected data are shown in Table 6.

With these corrections, the adjusted prediction equation becomes:

$$\mu Ci/liter\text{-}kt = 17(S)^{(-1.32)} \qquad (16)$$

This equation applies to cows eating green chop or pasture on farms in the path of maximum deposition from a fallout cloud.

The radioiodine concentration in milk would be increased by rainout or washout. For example, the snow-out effect in the Cabriolet data increased the concentration in milk by a factor of 4 (data from Mountain View Farm in Table 6). Studies of iodine-131 fallout in South Africa from French tests (VanAs and Vleggaar 1971) indicate that wet deposition increased the iodine-131 concentration in milk by a factor of 2. A summary of other published data suggests wet/dry deposition ratios ranging from 1.8 to about 10 (Black and McNelis, to be published). It would thus appear that increasing the radioiodine concentration, as calculated by the foregoing equations, by a factor of 10 would be a reasonably conservative action for estimating the effect of precipitation on deposition of radioiodine from a tropospheric cloud during the first few days.

## DOSE ESTIMATES

The predictive data just described can be used to derive dose estimates for the iodine-131 in thyroid glands which results from drinking contaminated milk. The equation from the International Commission on Radiation Protection Report Number 2 is used to calculate the infinite dose from a given quantity of iodine-131 in the thyroid. This equation for infinite dose, in rads, is:

$$D_\infty = 74(qf_2)\left(\Sigma EF(RBE)_n\right)T_{eff} \text{ rads} \qquad (17)$$

where $qf_2$ = fraction of body burden in the thyroid

$\Sigma EF(RBE)_n$ = energy absorbed per disintegration, in MeV

$T_{eff}$ = effective half-life of the isotope in the organ of interest, in days

A good summary of thyroid parameters is given in a paper by Wellman et al. (1969). If we assume the effective half-life in the thyroid to be 7.1 days, the energy loss per disintegration as 0.21 mega-electron-volts (MeV), and an

TABLE 6. MAXIMUM IODINE-131 IN MILK BY EVENT AND DISTANCE

| Event Name (feed type) | Yield (kt) | Farm Name | Distance From SGZ (km) | (mi) | Peak $^{131}I$ in Milk (nCi/liter) | (nCi/liter-kt) | (Corrected* nCi/liter-kt) | Cloud Burden† (kt) | Peak $^{131}I$ in Milk Corrected† (nCi/liter-kt) |
|---|---|---|---|---|---|---|---|---|---|
| Palanquin (fresh) | 4.3 | EPA | 4.5 | 2.8 | 2700 | 625 | 625 | | |
| | | EPA | 4.5 | 2.8 | 2300 | 535 | 535 | | |
| | | Martin | 217 | 135 | 11 | 2.56 | 2.56 | | |
| | | Boggio | 472 | 293 | 4.1 | 0.95 | 0.95 | | |
| | | Pasquale | 483 | 300 | 5.5 | 1.27 | 1.27 | | |
| Cabriolet (hay) | 2.3 | EPA | 4.5 | 2.8 | 0.84 | 0.365 | 5.10 | | |
| | | River Ranch | 435 | 270 | 0.16 | 0.070 | 0.97 | | |
| | | Mt. View | 441 | 274 | 0.63 | 0.274 | 3.83 | | |
| Buggy (hay) | 5.4 | EPA | 16 | 10 | 3.37 | 0.624 | 8.74 | | |
| | | Pohlsander | 467 | 290 | 0.55 | 0.102 | 1.43 | | |
| Schooner (hay) | 35 | EPA | 74 | 46 | 1.20 | 0.0342 | 0.555 | 0.133 | 126 |
| | | Lund | 219 | 136 | 0.063 | 0.0018 | 0.028 | | 6.6 |
| | | Boyd Schena | 402 | 250 | 0.10 | 0.00285 | 0.045 | | 10.5 |
| Pin Stripe (fresh) | low | Schofield | 101 | 63 | 4.8 | | | 0.0172 | 280 |
| Pike (fresh) | low | Habbart | 135 | 84 | 0.82 | | | 0.0064 | 124 |

* Corrected for type of feed
† Curies of $^{131}I$ divided by $1.25 \times 10^5$ Ci/kt
† Corrected for cloud burden and type of feed
SGZ = Surface Ground Zero

infant thyroid mass of 2 grams, then the equation becomes:

$$D_{\infty} = 74\left(\frac{\mu Ci}{2}\right)(0.21)(7.1)$$

$$= 55.2 \text{ rad}/\mu Ci \qquad (18)$$

The dose commitment to the infant thyroid can be calculated by using Equation 17 with the data in Table 4. The assumptions used to estimate the dose are:

1. Child drinks 0.7 liter per day, 0.35 liter from each milking;
2. First milking occurs 0.2 days (4.8 hours) after initial ingestion by the cow;
3. Negligible decay between milking and consumption;
4. Buildup between initial ingestion and peak concentration has an effective half-life of 1 day;
5. Fraction of ingested iodine in the thyroid is 0.3;
6. A peak activity in the milk of 1 microcurie per liter; and
7. Peak activity in milk occurs 2.2 days after initial ingestion and effective half-life is 4.7 days during continued ingestion, with cows on fresh feed.

The infinite dose for 47 days (10 half-lives) under the above assumptions is 91 rads. This dose changes directly with any change in thyroid uptake, effective half-life, peak concentration, or milk consumption.

From the calculated dose, the following data can be derived: buildup phase gives 11.9 percent of the dose, and total intake is 7.66 times the peak intake.

For cows on baled hay, the assumptions are the same except for the seventh which becomes:

7a. Peak activity occurs 4.2 days after initial ingestion and decreases thereafter with an effective half-life of 6.5 days during continued ingestion (assuming the effective half-life in milk equals that in hay).

Under these conditions, the infinite dose for 65 days of ingestion is 144 rads. Because of the longer time to the peak and the longer effective half-life, 23 percent of the total dose is acquired during the buildup phase, and the total intake is 12.4 times the peak intake. Thus, for equal peak milk concentrations, the thyroid dose is 1.6 times greater if the cows are fed contaminated hay rather than contaminated green chop. For a given contaminating event, though, the peak activity in milk from cows on green chop would be about 14 times that from cows on hay, and the infant thyroid dose would be about 9 times larger.

The infinite dose for continued ingestion of contaminated milk can be combined with the equations previously derived to yield predictive dose equations for the child with a 2-gram thyroid as follows. In these equations,

mR/h refers to the net survey-meter reading in milliroentgens per hour 1 meter above ground, IAC and F/C are derived from air sampler data, and kt is the predicted cloud burden of fission products in kilotons.

1. For cows on fresh feed:

$$D_\infty = 91(10^{-3})(4)(mR/h)$$

$$= 0.37(mR/h) \text{ rads} \quad (19)$$

$$D_\infty = 91(10^{-3})0.8\left(\frac{IAC}{F/C}\right)$$

$$= 0.072\left(\frac{IAC}{F/C}\right) \text{ rads} \quad (20)$$

$$D_\infty = 91(17)(s)^{-1.32}$$

$$= 1500(s)^{-1.32} \text{ rad/kt} \quad (21)$$

2. For cows on hay:

$$D_\infty = 144(10^{-3})(0.29)(mR/h)$$

$$= 0.042(mR/h) \text{ rads} \quad (22)$$

$$D_\infty = 144(10^{-3})(0.1)(IAC)$$

$$= 0.014(IAC) \text{ rads} \quad (23)$$

$$D_\infty = 144(1.22)(s)^{-1.32}$$

$$= 176(s)^{-1.32} \text{ rad/kt} \quad (24)$$

where rad/kt = rads per kiloton fission in the cloud

s = distance along the hot-line, in miles

The equations based on mR/h and IAC can be used at any location as long as the type of cow feed is known and the mR/h value used is the peak value or the value extrapolated back to H+6, whichever is greater. The two equations based on distance and fission yield, Equations 21 and 24, are more restrictive. They predict doses on the "hot-line" only and only for dry deposition with no meteorological concentrating factors. Also, for any of the equations, cows being fed fresh Sudan grass will transfer less iodine to milk, so the results obtained by use of the equations may be divided by 3.

## INHALATION DOSE

With these equations developed, the relative magnitude of inhalation exposure can be readily ascertained. Assume an effluent cloud passes over a dairy

farm where an infant resides, and assume an air sampler measures an integrated air concentration of 1.0 microcurie-second per cubic meter with activity in the filter equal to the activity on the charcoal. Also, assume that the infant is breathing at the rate of 15 liters per minute, or $2.5 \times 10^{-4}$ cubic meters per second ($m^3/s$), and that deposition in the lung is 100 percent with 100 percent absorption.

The inhalation dose, in millirads (mrads), then becomes:

$$(1.0\ \mu Ci\text{-}s/m^3)(2.5 \times 10^{-4}\ m^3/s)(0.3\ \text{uptake}) = 75\ pCi\ \text{in thyroid}$$

$$(75\ pCi)(55.2\ rad/\mu Ci) = 4.1\ mrads$$

The ingestion dose calculated from Equation 19 would be:

$$0.072\left(\frac{IAC}{F/C}\right) = 0.072(1)$$

$$= 72\ mrads$$

Therefore, under maximized conditions, inhalation adds about 6 percent of the dose caused by ingestion for cows on fresh feed and about 30 percent of the dose caused by ingestion for cows on hay. If deposition in lung and absorption is assumed to be less than 100 percent, then these calculated additional doses would be even smaller percentages of the ingestion dose.

## COMPARISON WITH OTHER STUDIES

A review of the literature indicates that many studies have been conducted on this subject, although very few have used data from actual field situations. Some of the published data are shown in Table 7. In general, there is no wide divergence in most of the parameters tabulated, although some of them differ significantly from the results reported here.

The effective half-lives for pasture, green chop, and milk reported in this paper require some comment. The pasture values were obtained by use of hand-cut samples from undisturbed pastures. Since pastures in the region are irrigated regularly and require scheduled applications of fertilizer, it is possible that growth may be more rapid, leading to dilution of the activity and a shorter effective half-life. On the other hand, green chop for cow feeding is generally cut only once a day, so loss of activity by growth of plants and physical dislodgement for that single day is minimized. This would result in a slightly longer effective half-life for the green chop and is reflected in the effective half-life for milk of 4.7 days. The 4.2-day effective half-life for pasture might have been observed in the milk had the cows been allowed to graze.

A comparison of some of the published dose-prediction equations with those developed in this report is shown in Table 8. There is general agreement of most items, which is somewhat surprising considering the variability of the

TABLE 7. COMPARISON OF VALUES REPORTED IN THE LITERATURE

| Reference | Time to Peak (days) | $T_{eff}$ Pasture (days) | $T_{eff}$ Milk (days) | % in Milk | Ratio of Peak Milk to Peak Forage | Remarks |
|---|---|---|---|---|---|---|
| Tamplin 1965 | 2-5 | | 4-6 | | | Review of previous literature |
| Sasser and Hawley 1966 | 2-3 | 5.5±0.7 | | 12.8 | 0.06-0.76 | Gaseous iodine release |
| Booker 1958 | 1.5-2 | 4.9 | 4.7 | | 0.09 | Windscale release |
| Thompson 1965 | | 5±1 | | | | Review of previous literature |
| James 1964 | 4.25 | 5 | 1.9 | 3.0 | 0.009 | Calculation vs. measured milk |
| Krapp 1963 | 4 | 4.9 | 5 | | | mR/h vs. peak milk activity |
| Comar et al. 1967 | 3 | 5 | | | | Oral doses |
| Lengemann and Comar 1964 | 2-3 | | | 4-24 | | Multiple oral doses |
| Garner et al. 1960 | 1-3 | | | 5.7-10.8 | | Multiple oral doses |
| Hawley et al. 1964 | 2 | 3.5 | 5 | 4.7 | 0.112 | Gaseous iodine release |
| Marter 1963 | | 5 | 4-5 | | 0.36-0.042 | Savannah release |
| Hull 1963 | | | | | 0.07 | Brookhaven data |
| Pendleton et al. 1963 | 9 | | 5.8 | | | Utah studies |
| Ekman et al. 1967 | 2-5 | | | | | Sprayed on pasture |
| Stigall and Leary 1966 | 5 | | 6 | | 0.302 | Prediction equations |
| Burton et al. 1966 | 2 | | | | 0.18 | Summary data |
| Soldat 1965 | 3 | 4 | 5 | | 0.07 | Gaseous from separation plant |
| This report | 2.2 | 4.2 | 4.7 | 8.9 | 0.07 | |

TABLE 8. COMPARISON OF PREDICTIONS FOR INFINITE DOSE TO A 2-GRAM THYROID

| Reference | Dose from 1-m γ* (rad) | Dose from 1 μCi/liter Peak Milk (rad) | Dose from 1 μCi/m² on Forage (rad) | Total Dose Divided by Dose from Peak Milk | Dose Prior to Peak (%) | $^{131}I$ in Milk or Forage | Remarks |
|---|---|---|---|---|---|---|---|
| James 1964 | $15.6R_0$ | 179 | | | | $87.5R_0$ | nCi per liter |
| Knapp 1963 | $(4.4\text{-}16.4)R_0$ | 128 | | | | $(26\text{-}96)R_0$ | nCi per liter |
| Comar et al. 1967 | | | | 11 | | | |
| Marter 1963 | | 240 | | | | | |
| Pendleton et al. 1963 | | 224 | | 13 | 33 | | |
| Stigall and Leary 1968 | | 436 | | 15 | | | Used 45% uptake |
| Burton et al. 1966 | | 340 | 48 | | | $1.5R_0$ | μCi per m² |
| Tamplin and Fisher 1966 | $3R_0$ | | | | | $0.1R_0$ | μCi per m² |
| Burton 1966 | | | 85 | | | | |
| Stocum 1968 | | 58 | | | | | Used 22% uptake, 0.62 liters per day |
| Soldat 1963 | | 156 | 11 | 8 | 4.1 | | Used 50% uptake, 1 liter per day |
| Federal Radiation Council #5, 1964 | | 143 | | 7 | 20-25 | | |
| This report: | | | | | | | |
| Fresh feed | $0.37R_p$ | 91 | 7 | 8 | 12 | $4R_p$ | nCi per liter |
| Hay | $0.042R_p$ | 144 | | 25 | 23 | $0.29R_p$ | nCi per liter |

* Gamma exposure rate measured 1 meter above ground; $R_0$ = mR/h at 24 h; $R_p$ = peak mR/h

data which form the basis of the equations. The differences, for the most part, are due to the assumptions for effective half-life in milk, milk consumption, and thyroid parameters used in making the thyroid dose calculations. The assumptions used in this paper are based on more recent data.

A comparison of the dose estimates, using the equations developed here, with those of Knapp (1963) and Tamplin (1966) for specific fallout situations is shown in Table 9. From this comparison, it appears that Knapp's dose estimates are too conservative. The estimates derived in our paper are almost identical to those of Tamplin. Marked differences in data are due to differences in cow forage. Tamplin's data apply to dairy cows on fresh forage, but it is reasonable to assume the forage was hay in St. George, Utah, during March when the Annie and Telsa detonations took place.

## OTHER RADIOIODINES

The data and equations used in the preceding portions of this paper apply to iodine-131. This is because iodine-131 was the easiest radioiodine to work with both for nuclear test effluent and controlled contamination experiments. However, the effluent from nuclear tests does contain other radioiodines, and in some cases useful data can be derived from the gamma spectrometric analyses.

The data available are from the three cratering tests (Cabriolet, Buggy, and Schooner) and from the accidental venting of Pin Stripe. These data and some of the parameters used for dose calculation are shown in Table 10. The cumulative dose to the infant thyroid from all radioiodine isotopes is shown in Figure 8. The dose is increased by 38 percent if the cows are fed contaminated green chop and by 12 percent if the cows are fed contaminated hay. In both cases, about 90 percent of this additional dose occurs in the first 4 days after a nuclear test.

## BANEBERRY DATA

After this paper was drafted, the Baneberry underground nuclear test accidently vented. According to the published report on this accident (Western Environmental Research Laboratory 1972), the McCurdy Ranch near Springdale, Nevada, had the highest reported iodine-131 concentration in milk. It is informative to apply the equations developed in our paper to the situation at the McCurdy Ranch.

The cows on this ranch were grazing a pasture at the farm. There were no survey-meter readings taken during or shortly after the deposition of radionuclide contamination. Furthermore, there were no air samplers operating there. The available data were integrated air concentration data from Scotty's Junction (about 23 miles northwest of the ranch) and Beatty (less than 10 miles south of the ranch), Nevada. The sums of the air sampler data plus an estimate of missing

TABLE 9. COMPARISON OF THYROID DOSE ESTIMATES IN RADS TO A 2-GRAM THYROID

| Location and Event Name | Exposure Rate (mR/h at H+24) | Peak or H+6 Exposure Rate (mR/h) | Knapp Estimate (rad) | Tamplin Estimate (rad) | Type of Feed | Estimate From This Report (rad) | Equation Used |
|---|---|---|---|---|---|---|---|
| Alamo, NV | | | | | | | |
| Small Boy | 0.09 | 0.61 | 0.4-1.5 | 0.27 | Fresh | 0.22 | 19 |
| Caliente, NV | | | | | | | |
| Small Boy | 0.08 | 0.43 | 0.35-1.3 | 0.24 | Fresh | 0.16 | 19 |
| St. George, UT | | | | | | | |
| Annie | 13 | 69 | 57-213 | 39 | Hay | 2.9 | 22 |
| | | | | | | 4.1 | 24 |
| Harry | 26 | 138 | 115-427 | 78 | Fresh | 50 | 19 |
| | | | | | | 71* | 21 |
| Tesla | 1.8 | 9.5 | 7.9-30 | 5.4 | Hay | 0.4 | 22 |
| | | | | | | 1.8 | 24 |
| Zucchini | 1.2 | 6.4 | 5.3-9.6 | 3.6 | Fresh | 2.3 | 19 |
| | | | | | | 62† | 21 |

* Perez and Robinson (1967) in estimating iodine-131 thyroid doses from milk samples collected at St. George, Utah, in 1953, obtain an estimate of 68 rad to the "standard" child thyroid.

† The high estimate obtained by using Equation 21, compared with that obtained from Equation 19, suggests that St. George was not on the "hot line" for this event.

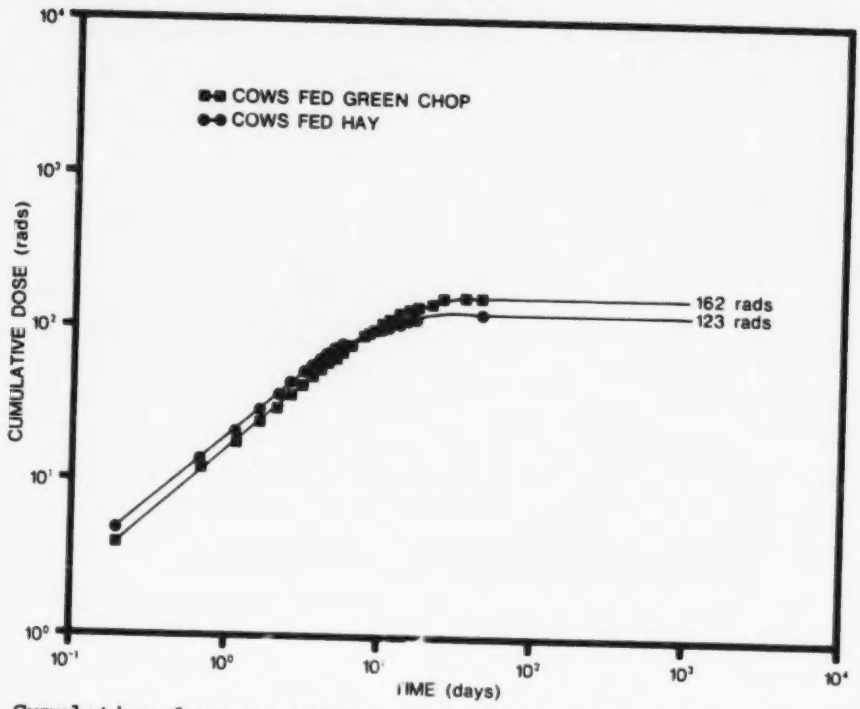


Figure 8. Cumulative dose to a 2-gram thyroid from radioiodine in milk ($^{131}$I peak = 1 μCi/liter with $^{132, 133, 135}$I in proportion; first milking 0.2 d after deposition; 0.7 liters/d consumed; no delay between milking and consumption)

TABLE 10. DATA ON THYROID DOSE CALCULATIONS FOR SHORT-LIVED RADIOIODINES

| Isotope | Time to Peak in Milk (days) | Ratio to $^{131}$I in Peak Milk | Teff in Milk (days) | Teff in Thyroid (days) | Absorbed Energy (MeV) | Thyroid Dose (rads/μCi) | Total* Dose (rads) |
|---|---|---|---|---|---|---|---|
| Cows fed hay: | | | | | | | |
| $^{132}$I | 2 | 3.1 | 2.25 | 0.1 | 0.59 | 2.18 | 3.7 |
| $^{133}$I | 1 | 2.1 | 1.0 | 0.84 | 0.49 | 15.3 | 11.7 |
| $^{135}$I | ND | ND | ND | 0.28 | 0.48 | 5.0 | 2.0 |
| Cows fed green chop: | | | | | | | |
| $^{132}$I | 2 | 3.0 | 2.0 | 0.1 | 0.59 | 2.18 | 5.5 |
| $^{133}$I | 1 | 3.3 | 1.0 | 0.84 | 0.49 | 15.3 | 20.8 |
| $^{135}$I | lst milking | 2.7 | 0.3 | 0.28 | 0.48 | 5.0 | 2.1 |

* total dose to a child's 2-gram thyroid; 0.7 liters of milk ingested per day; cows fed contaminated pasture continuously following a single contaminating event

ND = no data available

data, based on ratios, for the period of December 15 to 21, 1971 yield an IAC value of 0.61 microcuries per second per cubic meter for Beatty and 2.03 for Scotty's Junction. The filter-to-charcoal ratios were about 1 for both cases. Because McCurdy's Ranch is about one-fourth the distance between the two, we assume the IAC equals 1 microcurie per second per cubic meter. Because the cows were grazing, we use Equation 10. Thus, we would predict:

$$\text{peak nCi/liter} = 0.8\left(\frac{IAC}{F/C}\right)$$

$$= 0.8\left(\frac{1.0}{1}\right)$$

$$= 0.8$$

Thus we calculated a peak concentration in milk of 800 picocuries per liter which compares well with the 810 picocuries per liter measured.

The vegetation sampled at this ranch (rabbit bush and greasewood) had a peak concentration of 2.9 nanocuries per kilogram which, using Equation 12 and assuming the cow forage had the same concentration, would predict a peak concentration of 0.07(2.9) or 0.2 nanocuries per liter, a much lower value than the 0.8 calculated above. This confirms the unreliability of most forage sampling procedures.

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